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COSMIC RAYS AND ELEMENTARY PARTICLE PHYSICS*

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I. INTRODUCTION

THE advances in elementary particle physics over a period of more than thirty years are inseparably connected with the increase of the energy of the particles studied. There are two simple reasons for this connection. First, to produce new particles, in particular unstable short-lived particles, it is necessary to exceed the production threshold determined by the mass of particles of a given type—their rest energy. Second, to study their spatial structure it is necessary, if we take into account the wave properties of the particles, to use shorter and shorter waves (as in a microscope), i.e., higher and higher energies.

Accordingly, each new stage of elementary particle physics has been connected with the experimental surmounting of some energy threshold.

The sources of fast particles at all stages have consisted, on the one hand, of all of the laboratory sources—accelerators—which have been developed, and on the other hand—cosmic rays. Two processes have occurred in parallel: the energy of the particles furnished by accelerators has increased, and simultaneously the energy of the cosmic rays with which it has been possible to work reliably (in particular, measuring the energy and mass of the particles, emission angles, etc.) has also increased. Three basic regularities can be noted.

1. As a rule, the qualitatively new results, new particles, and new processes have been discovered in cosmic rays, and the detailed study of the phenomena has been completed in accelerators. Independent, qualitatively new results have been obtained in accelerators only in the last decade.

2. This relation of the roles of the two methods of investigation has resulted from the fact that the characteristic cosmic-ray energy with which effective studies have been carried out at a given moment has always been about two orders of magnitude higher than the energy of particles produced at the same period by the best accelerators. However, in the study of specific problems (for example, in the measurement of the total cross section of certain interactions) the lead is as much as 5—6 orders of magnitude at the present time.

3. The energy region in which intensive studies have been made has been advanced by $1\frac{1}{2}$—2 orders of magnitude in the last decade. From the beginning of the 1930's to the present time it has increased from 0.5 MeV to 3×10^4 MeV in accelerators, i.e., by $\sim 10^5$ times, and from ~ 5 MeV (the discovery of the positron) to $\sim 10^6$ MeV in cosmic rays, i.e., also by $\sim 10^5$ times. We can mention one more fact. Although cosmic rays are very inconvenient as an object of study—they are uncontrolled, many parameters are often unknown and consequently the experiments are not completely unique, and the like—there still has not been a case in which a fact established in cosmic rays and widely accepted by cosmic-ray experimenters has not been subsequently confirmed in accelerators.

These regularities can be traced step by step.

At the beginning of the 1930's the positron was discovered in cosmic rays, and relativistic quantum mechanics became a well established science. This was due to the surmounting of the energy threshold (in the laboratory system) $E_L \gg mc^2 \approx 0.5 \times 10^6$ eV, where m is the electron mass. Detailed verification of the theory was achieved within the following decade by means of laboratory sources of high energy particles.

In the following years there were doubts (unfounded, as we now know) as to the applicability of quantum electrodynamics in the energy region $E_L \gg 137\ mc^2$. These doubts were refuted and the validity of the theory confirmed in the middle of the 1930's as the result of studying electromagnetic cascade showers in cosmic rays.

At the same time the transition to this energy region implied also the transition to $E_L \gg \mu c^2$, where μ is the meson mass. Accordingly, the μ meson was discovered in cosmic rays, its instability was observed, and its mass and lifetime measured. Although this discovery was considered a brilliant confirmation of Yukawa's hypothesis of nuclear mesons, even then, at the end of the 1930's, it was demonstrated in cosmic rays that there was a major discrepancy, suggesting that in addition to μ mesons there were other, nuclear-interacting mesons with a lifetime two orders of magnitude shorter.

These particles—π mesons—and many others were discovered in cosmic rays in the period 1947-1950. These particles were found in accelerators only with the mastery of the energy region above their production thresholds in the center-of-mass system of the colliding nucleons, $E_c - Mc^2 \gg \mu c^2 \sim 10^8$ eV, E_c

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$= \sqrt{1/2\,(E_L + Mc^2)Mc^2}$ (M is the nucleon mass), i.e., $E_L \gtrsim 10^9$ eV in the laboratory system. Many meson decay schemes, lifetimes, masses, and a rough estimate of the interaction strength were determined in cosmic rays.

Hyperons were found in cosmic rays at the same time and somewhat later. In accelerators this required achievement of an energy $E_c \gg Mc^2$, i.e., $E_L \sim 10^9$—10^{10} eV. The phenomena leading to the concept of strangeness were discovered in cosmic rays. It should not be forgotten that even the question of parity nonconservation was raised by data on K decay in cosmic rays.

The study of interactions at $E_L \gtrsim 10^{10}$ eV simultaneously led to discovery of multiple production of mesons in a single event, a fact crucially important for the theory. Subsequently, with the appearance of accelerators in the region of $(1-3) \times 10^{10}$ eV, this entire field of strong interactions was transferred into the hands of accelerator physicists, using much more reliable and precise methods, and a series of new, detailed results was obtained.

Of course, this approach to the study of elementary particles does not encompass everything. Given sufficient precision of measurements, it is not always necessary to exceed a definite threshold to obtain fundamental results. There is what we may call the Michelson approach, used in development of the theory of relativity. Here an effect is measured, say, with a value $v^2/c^2 \sim 10^{-8}$, but because of the accuracy of the experiment this is sufficient to establish a physical result. Similarly, the shift of the levels in the hydrogen atom, measured for a value α^2Ry $\sim 10^{-4}$ eV and determined with an accuracy of 10^{-4} of this value, is a confirmation of relativistically invariant quantum electrodynamics, a confirmation most important for the theory of elementary particles. But in the case of threshold effects such as discovery of new particles or multiple production, the transition to high energies is often unavoidable.

The success in constructing proton accelerators with laboratory energies of 10—30 BeV and the extremely valuable results obtained with them in recent years has drawn attention away from cosmic rays as a source of information on elementary particle physics. The opinion has spread that we have already achieved the energy region which will provide all the necessary data, since it has become possible to study nucleon collisions at $E_c \sim 5$ BeV, which greatly exceeds the nucleon rest energy.

However, it appears that some change in this point of view has been noted recently. Therefore it is advisable to discuss the question: Do there exist among the fundamental problems of elementary-particle physics some whose solution, in the first place, requires a transition to higher energies than produced by contemporary accelerators and, in the second place, some which could be solved by means of cosmic-ray physics?

2. GENERAL NATURE OF THE PRESENT-DAY PROBLEMS OF ELEMENTARY PARTICLE PHYSICS

The present-day problems in the theory of elementary particles center mainly around three closely related fundamental questions.

1. Is the interaction of fields in an arbitrarily small space-time interval completely local or, on the other hand, is it somehow disturbed beyond a threshold of certain extremely small distances or time intervals, for example, so that at these extremely small intervals propagation of a signal takes place with a velocity exceeding the velocity of light in vacuum, c? This question is sometimes formulated as follows: Does there exist some new fundamental universal constant l_0, unknown to us, very small in absolute value, with the dimension of length or time? If it exists, it follows that the ordinary formulation of the principle of causality, according to which it is impossible to transmit an interaction with a velocity greater than c, is violated "in the small." This problem can also be stated in the following way: Is the contemporary quantum theory of relativistic fields, based on the principles of localizability and causality, incorrect in its basic assumptions, or is the theory correct, but we do not know how to apply it properly, for example, we simply do not know how to solve equations including strongly interacting fields (since here there is no small parameter, and perturbation theory, which is suitable for ordinary electrodynamics, is inapplicable)?

2. Of what nature is the structure of elementary particles and what is responsible for it? What is the spatial distribution of the properties (charge, magnetic moment) in the different particles and the distribution of their fields in interactions? What is the mechanism of their interaction, and the mechanism of new particle production at high energies?

3. The question of questions: How can we understand the existing spectrum of masses, spins, charges, and parities of particles, and what is the dynamical nature of this diversity of particles?

Of course, in approaching these lofty, all-encompassing goals, the problem reduces for the most part to finding the mutual forces and theoretically describing the specific interaction processes of different types of particles at different energies, studying their cross sections, masses, spins, and other particle properties, and the like.

The investigations pursue all of these directions. As we all know, the last year has been marked by rapid development and considerable success in construction of a phenomenological scheme of the existing particles and their systematics based on the symmetry properties discovered for the particles. Thus, we have been able to obtain formulas which reproduce with amazing accuracy the measured ratios between certain elementary particle characteristics which previously had remained completely unconnected.

Which of the problems in these three fields can be clarified by cosmic-ray studies?

Of course, we must be guided here mainly by a general principle: these investigations, which deal with an uncontrolled, unregulated, and difficult-to-detect source, have always given and apparently will always give in the future mainly those results not involving the precise measurement of small quantitative effects. We must not, however, forget that although these rough experiments constitute the main prerogative of cosmic rays, in many cases cosmic-ray experiments give rather accurate quantitative results.

As examples we can mention that the constancy of the cross section for interaction of nucleons with the nuclei of atmospheric atoms was established by experiments with cosmic-ray extensive air showers in the energy range $10-10^6$ BeV with an accuracy of the order of 30%, that the constancy of the average transverse momentum of particles created in a multiple production process in the energy range $5-10^4$ BeV was established with still greater accuracy, and so forth. Recently built apparatus and new apparatus being built or planned, using a cloud chamber in a magnetic field with assorted electronics, permit study of interaction events at energies of the order of 5×10^{11} eV at the rate of thousands per year. A less complete analysis is allowed by nuclear emulsion studies in the energy region up to 10^{13} eV and above, and so forth.

3. NEW PARTICLES

First of all we must dwell on the problem which is traditional for cosmic-ray physics—the possibility of finding new particles. This problem takes on particular importance at the present time as the result of the recent successes in the theory of elementary particle symmetries. We cannot discuss the question of symmetries here. It is important to note that in its very general formulation it is based on the concept of certain primary particle-fields, from the coupling of which arise the particles observed by us. A very simple variant of the proposed systematics involves quarks—particles with fractional charges $\pm {}^2\!/_3 e$ and $\pm {}^1\!/_3 e$, where e is the elementary charge. Fractional charges can be eliminated from the theory by application of an additional constraint, for example, introduction of some new quantum number. But even in this case the question remains of new "basic" particles with integral charge, different from particles observed up to the present time. They may be stable, have a mass greater than the nucleon mass, and appear in a different type of strong interaction. The search for these particles in cosmic rays is an extraordinarily important and very attractive problem. Attempts to search for them in accelerators have given negative results. This may mean, however, only that their mass is very great and therefore that it is particularly necessary to use cosmic rays.

Then there is the problem, raised by weak interaction theory, of the search for the heavy boson; we will say something about this later on.

Finally, we must mention the searches for the Dirac monopole, carried on unsuccessfully for many years. More than thirty years ago Dirac turned his attention to the fact that quantum mechanics opens up the possibility of the existence of a particle with a magnetic charge of a perfectly definite value. Its properties have been studied theoretically.

In this connection Dirac is reported to have said: "It is difficult to imagine that nature has not utilized this possibility." The difference from the problem of quarks or other basic particles lies in the fact that the magnetic monopole is an isolated possibility, not necessary for any theory, just merely possible. In the meantime the basic particles are an important element of the entire study of symmetries, which although far from complete is very attractive and up to the present time has produced many remarkable results.

In completing this enumeration of possible new particles, we can list here also an object which according to numerous data has already been noted in cosmic rays. There is weighty evidence that in a collision of nucleons with energies above 20—30 BeV in the center-of-mass system ($3 \times 10^{11}-10^{12}$ eV in the laboratory system) mesons are produced preferentially in the form of rapidly decaying clusters of many (~ 10?) particles. Evidently these clusters, if they actually exist, merit the name particles to the same extent as the resonances already found in accelerators, which decay into two, three, or even four π mesons.

Let us turn now to a systematic review of the different interactions.

4. CLASSIFICATION OF FIELDS

In elementary particle physics it is necessary to deal with interactions of three types:

a) Strong or mesonic interactions, characteristic of nucleons, π mesons, hyperons, etc. The typical cross section for this interaction of particles at energies much greater than their rest energy is nearly constant and is of the order of 10^{-26} cm^2 (for example, for elastic pion-nucleon scattering in the extreme relativistic region $\sigma \approx (0.5-1) \times 10^{-26}$ cm^2).

b) Electromagnetic interactions, which play the principal role for electrons, positrons, μ mesons, and photons interacting with them. Their cross sections often fall with energy, and at energies of the order of the rest energy of the particles they are usually less than the cross sections of strongly interacting particles (but, for example, for scattering of a photon of very high energy E by a stationary electron, $E \gg mc^2$, we have $\sigma \approx 25 \times 10^{-26}\, mc^2/E \times \ln(E/mc^2)\ cm^2$).

c) Weak interactions, characteristic of the interaction of the neutrino with other particles. According to theory, up to an energy (in the center-of-mass system) of the order of 300 BeV these cross sections increase rapidly with energy, but are still very small. (For scattering of a neutrino with energy E by a stationary electron $\sigma \approx 5 \times 10^{-45}\, E/mc^2\ cm^2$.)

We will analyze the problems and possibilities of cosmic ray physics for each of these types of forces We will see that for the electromagnetic interactions the possibilities here are limited, but for the strong and weak interactions cosmic rays apparently remain irreplaceable in a number of respects, until new accelerators are built with energies several orders of magnitude higher than those of present accelerators. This cannot possibly occur sooner than in 10—15 years.

5. ELECTROMAGNETIC INTERACTIONS

The theory of the purely electromagnetic interactions—quantum electrodynamics—is the most developed and most systematic theory of quantum fields. Although there is a certain inadequacy in its fundamental bases, it is very well confirmed in many details by all known experimental data. In addition, since there are particles, electrons and μ mesons of both signs, for which the electromagnetic interactions are the principal ones (they are many orders of magnitude more important than the other interactions for these particles), verification of quantum electrodynamics in experiments with these particles is a beautiful possibility of verifying certain basic postulates of the theory such as localizability and causality at small distances, and so forth. In quantum electrodynamics these particles stand out as practically point centers for which the field and the interaction can be calculated with any desired accuracy. The search for a breakdown of this field at small distances is possible, on one hand, by looking for the contribution of these breakdowns to the properties of an individual particle—for example, to its magnetic movement or to the energy of its stationary states (a shift of an electron level in the hydrogen atom), for which high energies are not required at all; and on the other hand, from study of the mutual scattering, annihilation, etc., of these particles. In the last case, the higher the energy, the smaller the distance studied. (As we have said above, this is exactly like a microscope. Since the object of study experiences appreciable recoil, we are concerned with the energy in the center-of-mass system of the colliding particles.)

At the present time the best results on this question are given by an extremely precise measurement of the μ-meson magnetic moment (the value of g-2, the Lande g factor, has been measured with an accuracy of a small fraction of a per cent). This is an experiment of the "Michelson type" in the sense mentioned above. With the present experimental accuracy, this measurement does not reveal any departures from ordinary quantum electrodynamics down to distances of the order of 10^{-14} cm. A similar limit to the validity of the theory is given by experiments on the scattering of electrons and muons by protons (where it is necessary, however, to take into account the smearing out of the proton charge), on the production of μ-meson pairs with large separation angles by 5-BeV photons, and the like.

All of these experiments give precise results which cannot be matched by cosmic rays. This is not their field.*

Nevertheless we can already point to at least one particular specific effect of interest for the theory. It has been observed that μ mesons of extremely high energy, penetrating deep into the earth, produce π mesons. This is explained by the fact that at such a high energy, $E \gg \mu c^2$, the relativistically contracted electromagnetic field of the meson has essentially the features of a packet of high energy photons: the field is almost exactly transverse and the magnetic vector in it is perpendicular to the electric vector. These "photons" cause photoproduction of pions in the nuclei of the medium Therefore study of the effect allows us to draw conclusions as to the cross section σ for the process: γ + nucleon = nucleon + pion. Some years ago an indication was obtained in cosmic-ray work that this cross section at a pseudophoton energy $E \gtrsim 10$ BeV is not greatly different from the photon cross section measured in accelerators, i.e., for $E \lesssim 0.5$ BeV (here it is necessary to have electron accelerators, which only recently have

*It is true that there is an interesting class of electromagnetic phenomena which are impossible at low energies. These are phenomena connected with the fact that production of bremsstrahlung, electron pair production, scattering in a Coulomb field, etc., for superhigh energies E occur at neglibibly small angles $\theta \sim mc^2/E$, i.e., for $10^{12} - 10^{15}$ eV, $\theta \sim 10^{-6} - 10^{-9}$ radian. As in the optical diffraction by a grating, which occurs for grazing incidence of x-rays onto the surface, here each elementary act takes place over a very large region encompassing a very large number of atoms. For this reason the usual processes change their nature sharply if they occur not at an isolated atom in a gas but in a dense medium. The effects predicted by a number of theoreticians were observed in cosmic rays, and now some of them apparently will be used in accelerators, for example, to obtain monochromatic photons, and the like. It is interesting that the wave properties of the particles show up here only at high energies, i.e., at small wavelengths. However, while elegant in themselves, these pheomena have contributed nothing to the fundamental problems of elementary particle theory.

reached the 5-BeV region). However, these measurements are rather difficult in cosmic rays, and the effects of nucleon size and of the longitudinal part of the electromagnetic field have not been very reliably calculated. Therefore the indication obtained cannot be considered as certain. Here it is preferable to speak of the real prospect for obtaining a value important to physics at an energy inaccessible to accelerators. It is to be expected that other similar possibilities will be found of studying individual electromagnetic processes at superhigh energies in cosmic rays.

6. WEAK INTERACTIONS

Interactions of the neutrino type are among those which are exceptionally important for theoretical reasons. These interactions, which have been well studied at low energies of the order of one MeV, are described quite differently from the electromagnetic or strong interactions. Specifically, the primary elementary process in this theory is the transformation of two Fermi particles into two similar or different Fermi particles. For example, in terms of Feynman diagrams, the scattering of a neutrino by an electron is the process shown in Fig. 1, which cannot be broken down into simpler processes. At the same time, however, the scattering of a photon by an electron and in general any electromagnetic interaction contains only triple vertices—Fig. 2. Thus, the elementary event is the interaction of a Bose particle (photon) with a Fermi particle (electron), giving a Fermi particle. Only triple vertices enter into meson-nucleon interactions. This difference is basic: the four-fermion interaction is nonrenormalizable.

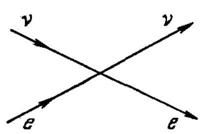

FIG. 1

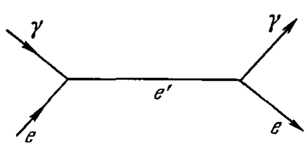

FIG. 2

This means that the infinities encountered in the theory cannot be eliminated, or removed from specific calculations so cleverly or so uniquely and with relativistic invariance as in the electromagnetic and strong interactions. This feature has a very deep significance. On the one hand, it has been used by Heisenberg in his attempt to construct a unified field theory of all particles. On the other hand, there is a tendency to get rid of this peculiarity of weak interactions. The hypothesis has been advanced that some still undiscovered particle exists, an electrically charged boson—the W meson, which forms an intermediate link in weak interactions. It has been suggested, for example, that $\nu e \rightarrow \nu e$ scattering proceeds in reality according to the diagram of Fig. 3.

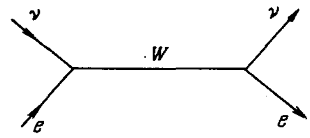

FIG. 3

As a result the theory becomes a theory of a more usual type (to be sure, it has not yet been possible to introduce the W meson in such a way that the theory become renormalizable).

Searches for W particles in the free state have been made with accelerators, but unsuccessfully. It has been concluded that if this particle exists, its mass is greater than ~ 4 nucleon masses. In this case, if we take into account the kinematic relations characterizing its production process, it must be looked for at the energy limit of the largest presently existing accelerators or at still higher energies, and cosmic rays are necessary here.

There is another means of ascertaining the validity of the four-fermion theory of weak interactions. Its specific nature results in an increase of the cross sections in proportion to the particle energy. For a center-of-mass energy of 300 BeV (10^{14} eV in the laboratory system) this increase must lead to the failure of perturbation theory and an importance of multiple processes as great as that of the simplest possible processes (however, their cross section uniformly remains extraordinarily small). Verification of this simple question—do the weak-interaction cross sections increase with energy in the supra-accelerator energy region?—is therefore of exceptional interest for theory. A direct verification of this type is evidently possible only in cosmic rays. These extraordinarily difficult investigations have already been started. They are difficult because the measured cross section is negligibly small (10^{10} or more times smaller than for ordinary mesons), and the flux of neutrinos of such high energy in the atmosphere is negligibly weak*. To be sure, an approach of the Michelson type is also possible here. We can calculate theoretically what distortions in the properties of a charged particle, for example a μ meson or an electron (in the magnetic moment and the like), is introduced by an admixture of weak interactions. They would correspond to distortion of the particle field at distances of the order 10^{-16} cm. However, in contrast to electrodynamics, the theory of weak interactions cannot give exact, quantitative predictions here just because it is "poor," i.e., unrenormalized.

*In these experiments, which are carried out deep underground (in order to be shielded from the flux of interfering particles and to observe only the effect produced by the neutrino), the effective area of the scintillation counters amounts to hundreds of square meters.

It is evident from what we have said that experiments with neutrinos of supra-accelerator energies have a tremendous value to the theory.

7. STRONG INTERACTIONS

If the energy of two colliding strongly interacting particles is sufficiently great, then there are produced in one event not one but many new particles—pions, nucleon pairs, and so forth. This is a most important feature of strong interactions (it is just for this reason that they are called "strong"). On the other hand, this is not true in the electromagnetic interactions: the probability of radiation of two photons in a collision of an electron with a nucleus, as a rule, is two orders of magnitude smaller than the probability for radiation of one photon, as a consequence of which the electromagnetic processes can be calculated extremely accurately—perturbation theory is applicable here. The importance of this fact is so great that where it is not true—in the radiation of extremely soft photons (which is of little practical importance), the expression "infrared catastrophe" is used. In the field of strong interactions, as had already been observed in cosmic rays in the 1940's, this "catastrophic" situation always occurs. Therefore, although the equations of the theory can be formally written down and the Lagrangian of the interaction is apparently known, the advantages of this are not very numerous. We do not know how to calculate convincingly and rigorously multiple processes which occur either explicitly, like the phenomenon of multiple pion production, or hidden in a chain of calculations, like the polarization of the nucleon-meson vacuum and of the similar "virtual states." Furthermore, the basic foundations of the theory (from consideration of which we can depart in electrodynamics, having begun a course of renormalizations) are subject to serious doubt in the case of the strong interactions.

Therefore here, in expectation of a future correct and general theory, one looks for particular methods adapted to specific problems. Assuming the possibility that the general equations of quantum field theory are perhaps unsuitable here in their foundations, one uses not these equations but certain relations, less meaningful, but in return based only on the general principles of localizability and causality, for example the so called dispersion relations and the like. Each particular theoretical hypothesis which goes beyond the framework of these general relations presents special interest as a possible building block of the future theory and is subjected to serious experimental verification. Few of these hypotheses have stood up long under experimental test. It is noteworthy, however, that where these general relations of field theory, which are considered as certainly true, have been used, they do not contradict experiment. The situation described obviously presents the greatest scientific interest: The experimental indications in combination with analysis of hypotheses put forward, models, and approximations to rigorous relations, take on enormous significance.

Interest in cosmic rays as a method of elementary particle physics, as we have said, has decreased in the last 5—8 years, when accelerators appeared for nucleons to 10—30 BeV, i.e., $E_c \sim 3-5$ BeV in the center-of-mass system of the two colliding nucleons. It appeared that we had passed the last natural energy threshold, $E_c \sim 1$ BeV $\approx Mc^2$. Strong interactions became accessible to precision laboratory investigations in the relativistic region, and one could think that further increase of energy would give nothing fundamentally new. This point of view was strengthened by the very important data contributed by cosmic rays themselves. As we have already mentioned, cosmic-ray studies showed that the cross section for interaction of nucleons with nuclei of atmospheric atoms remains constant up to energies of the order of $E_L \sim 10^{15}$ eV. Consequently, it does not change (or changes very weakly) when the energy changes a millionfold.

However, just those accelerator studies which have recently contributed so much of value, having confirmed in particular the previously obtained data of cosmic-ray physics, have confirmed also the indications of the incorrectness of this quieting idea.

From the point of view of the data obtained in accelerators, three facts are important here.

The first fact is the history of the Regge pole method. Three years ago there was advanced and then widely developed a very elegant and apparently very promising special theory based on a definite hypothesis as to the properties of the amplitude of a wave elastically scattered in the collision of strongly interacting particles. The hypothesis was of a rather formal nature, was phenomenological, and discussed what singular points (in the complex orbital momentum plane, which does not have a direct physical significance) could be possessed by an elastic-scattering amplitude. This theory led to some quite specific predictions of the properties of the elastic scattering of particles and of the total (including inelastic) cross sections for interaction of particles of different types. From the beginning, accelerator experiments brilliantly confirmed the predictions of this theory in the case of elastic proton-proton scattering. However it later turned out that the scattering of other particles (π^+-proton, π^--proton, K^--proton, antiproton-proton) do not have the required nature at all. Meanwhile, the most important conclusion of the theory was the universality of elastic scattering for particles of any type, if we are concerned only with strong interactions and if the energy is much greater than the rest energy. This result shows that:
a) either the hypothesis as to the properties of the singular points is incorrect in principle or b) the energy region studied is too small, and we are not

yet in the asymptotic region. We will discuss later how else this result can be understood if we are not limited to the phenomenological interpretation, and attempt to find the interaction mechanism. For the present we can state that even from the point of view of this approach, sufficiently high energies have not been attained in the accelerator region and it is necessary to go to higher energies.

The second fact is that measurement of total cross sections for the interaction of particles of different types has shown that in most cases, even at ~30 BeV, they still do not satisfy the relation derived from the general propositions of the theory and called the Pomeranchuk theorem. According to this theorem, if the total cross sections reach a constant value with increasing energy, the cross sections for collision of particles and antiparticles must become equal, i.e., we must obtain

$$\sigma_{AB} = \sigma_{\bar{A}B},$$

where A and B are particles, and $\bar{A}$ is an antiparticle. Neither the constancy of the cross sections nor this equality of cross sections exists at 30 BeV, i.e., in accelerator experiments.

The third fact is that from rather general propositions of the theory the conclusion has been drawn that with increasing energy we must asymptotically achieve one important property of the elastic scattering amplitude—it must become almost pure imaginary. (This property has a simple physical meaning: The pure imaginary amplitude for scattering by a black sphere, i.e., the diffraction amplitude, is entirely due to absorption and inelastic processes. Scattering in a transparent, nonabsorbing medium or scattering of particles in a potential field has a real amplitude.) Experiments in accelerators have shown that even at 30 BeV the real part of the amplitude still amounts to 30% of the imaginary part, i.e., it is not small.

All of these three facts show that it is insufficient to reach an energy much greater than the proton rest energy in order to be in the asymptotic region, and that no "simple" properties of the elastic scattering process and the interaction appear yet even at 30 BeV.

This means that, in addition to the energy threshold $E \sim Mc^2$, there may exist some new threshold located still higher. Indications of its existence can be obtained from the following considerations.

In the first place, both in the Regge pole method as applied to elastic collisions, and in an approximate method of treatment of strong interactions which we will discuss later, a characteristic parameter $\ln(E_L/Mc^2)$ appears in the one-meson approximation. The characteristics of the process change noticeably only when $\ln(E_L/Mc^2)$ becomes greater than 1. If we require $\ln(E_L/Mc^2) \approx 4$, we obtain $E_L \sim 10^{11}$ eV.

In the second place, the average multiplicity of production, as shown by cosmic-ray experiments, increases with energy roughly as

$$\bar{n} \sim \left(\frac{E_L}{\mu c^2}\right)^{1/4},$$

and the average number of particles created in one event, $\bar{n}$, has an order of magnitude of five for $E_L \sim 10^{11}$ eV. Therefore such an important property as the simultaneous production of very many particles appears only in the supra-accelerator region.

In the third place, as we have already mentioned, weighty evidence has been obtained in cosmic rays that in a collision of two nucleons the π mesons produced are emitted not directly by the nucleons but by some cluster of mesonic matter, separated from the two nucleons, this phenomenon setting in at $E_L \sim 10^{11}-10^{12}$ eV.

All this compels us to suppose that in going to an energy of the order of $10^{11}-10^{12}$ eV we can expect new results of considerable interest for elementary particle physics. This region will remain inaccessible to accelerators for a number of years yet.

In order to understand in more detail the problems arising here, let us consider the mechanism of interaction of nucleons and high-energy pions.

First of all we must recall that, in contrast to electromagnetic interactions, each source of a strong meson-nucleon field, for example a nucleon, creates around itself a strongly perturbed region of vacuum—a cloud of virtual pions, nucleon-antinucleon pairs, and so forth. This cluster of meson-nucleon matter has a spatial structure which has already been rather well explored, for example, by scattering of electrons with energies of the order of 1—5 BeV in accelerators, and more roughly by other methods. This cluster, which represents a real physical nucleon, is thinned out at the periphery where the probability of observing not more than one π meson is large. The mean radius of a physical nucleon is about 0.8×10^{-13} cm. The radius of a pion evidently is roughly of the same order, but we have not been able to study the pion by probing it with fast electrons, as has been done for the nucleon: The pion is unstable, its lifetime is of the order of 10^{-8} sec, and it cannot serve as a target in direct experiments.

A high-energy nucleon is relativistically contracted in the direction of motion: the nucleons in accelerators are contracted by 10—30 times, and in cosmic rays nucleons are studied with energies of 10^{15} eV or higher, which are thin sheets whose thickness is a million times smaller than their diameter.

The smearing out of the nucleon leads to the following important fact: direct collisions of strongly interacting particles cannot so simply bring us closer to observation of nonlocalizability or of the existence of a fundamental length, if it is less than 10^{-13} cm (and experiments in electrodynamics show, as we have already said, that is is less than 10^{-14} cm). In fact, even for a collision parameter of the order of 10^{-13} cm, when nucleons graze each other only with their "edges," their interaction is already so strong that multiple production of particles occurs.

It must be emphasized that it was long ago observed in cosmic rays (at first in the energy region of the order of 10 BeV, and later at somewhat higher energies) that these processes of multiple production of π mesons in a collision of nucleons, as a rule, do not disturb the fundamental state of the colliding nucleons: they retain more than half of their initial energy and are emitted in the forward direction. It can be said that nucleon collisions, as a rule, occur with an impact parameter of the order of 10^{-13} cm (which also gives a collision cross section $\sigma \approx 4 \times 10^{-26}$ cm^2) and are not catastrophic for the nucleons. These collisions are called peripheral. However, a wide spread in the characteristics of the collision event is typical, and evidently "central," catastrophic collisions also exist which lead to formation of a single system from which particles are also radiated.

The isolated nature of peripheral collisions, which perturb the nucleon only weakly, is an experimental fact which has been observed with a considerable degree of conviction also at low energies, of the order of 2—5 BeV. In this connection an approximate method has been developed of describing the production of π mesons in nucleon collisions. It is called the one-meson-exchange approximation and can be symbolically described as the exchange of one meson between the colliding particles (Fig. 4).

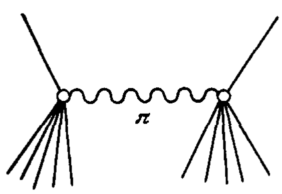

FIG. 4

It can be described also in this way: each nucleon most frequently strikes the periphery of the other nucleon, and here it encounters a thinned out pion cloud in which it collides with only one pion. Another limiting case in principle is the exchange of so many π mesons that the interiors of "cores" of the nucleons are themselves drawn into the general interaction. This leads to a process of a completely different type. It was considered more than ten years ago by Heisenberg, Fermi, and Landau. And although up to the present time we have not obtained completely convincing proofs of its existence in the cosmic-ray region, it is so important and interesting that we must discuss it here.

The theory created by these authors for this process proceeds from the idea that in one event the colliding nucleons exchange their energy between a large number of generated particles (and in cosmic rays cases are encountered with production of many tens of particles). A system is formed with many degrees of freedom, which can be treated statistically and thermodynamically. This is a black body, to which we can assign a temperature, and the π mesons emitted by it must be distributed in energy according to Planck's formula. Landau took an important step in this theory by including the strong interactions between the emitted particles themselves. Formally this implies consideration of the dispersing cloud of meson-nucleon matter according to relativistic hydrodynamics with a definite equation of state.

The nonquantum, hydrodynamical treatment of processes inside a nucleon, which is still contracted to a thin sheet, is in its elegance an amazing example of the systematic application of the principles of physics. For all its paradoxicality, this approach is completely exact and systematic. It is hypothetical only because it assumes: a) that such a state actually arises at the initial moment of the collision—and this has not yet been proved by experiment: in most cases a nucleon-nucleon collision is peripheral; b) that the processes are completely local, that there is no fundamental length, and therefore it is permissible to consider arbitrarily small volume elements; furthermore, the specific formulas of the theory include two particular elements; c) a specific equation of state; however, the theory was later generalized by Milekhin to any equation of state; d) that viscosity does not play a role; this assumption is apparently incorrect; inclusion of the viscosity leads to a change in certain specific formulas (some change in the multiplicity of production and in the separation angles), which, however, does not have a fundamental significance.

If we accept the two initial hypotheses mentioned, namely first, that among the inelastic processes in addition to peripheral, one-meson processes at arbitrarily high energies there exist also central, hydrodynamical processes; and second, that the elastic scattering amplitude at superhigh energies, as seems extremely probable (see above), is pure imaginary, then it is possible to reach very interesting conclusions. Proceeding from general relations for the amplitudes of the processes, we can systematically connect the elastic and inelastic scattering so as to trace what properties of elastic scattering result from inelastic interactions of the peripheral type, on the one hand, and from collisions of the central type on the other hand. It turns out that peripheral inelastic collisions lead to elastic interactions of the Regge type, and central interactions to non-Regge elastic interactions. This brings to light a possible cause of the failure of the Regge method, of which we spoke above: it takes into account only part of the processes, only those which are due to peripheral inelastic collisions. And the admixture of central collisions is different for different particles.

This point of view has found confirmation in the results of cosmic-ray experiments: in cosmic-ray work on inelastic interactions it has been estimated that peripheral collisions do not play as great a role in pion-nucleon collisions as in proton-proton collisions. According to this, elastic scattering should have a Regge character for proton-proton collisions, but not for pion-proton collisions. This has been found in accelerator experiments.

In addition, it follows from the same investigation that at superhigh energies π mesons should be produced as clusters of mesonic matter which decay independently to π mesons and have a mass several times larger than the nucleon mass. These clusters, as we have said, have apparently been observed in cosmic rays, although not as yet with great certainty. They have received the name fireball. However, they can be produced away from nucleons only at very high energies—of the order of 10^{11}—10^{12} eV, and the number of them increases very slowly with energy.

Thus, we arrive at an interesting picture which in many ways corresponds to the experimental data. We can see from this how important it would be to establish whether or not central collisions of a hydrodynamical type exist (in the theory described it is important that they exist, if only for pion-pion collisions).

It follows from what has been said that as we go to supra-accelerator energies we can expect the continuing discovery of new and interesting features of strong interaction processes.

8. CONCLUSION

During more than three decades, investigations in the field of cosmic rays have played a major, pioneering role in elementary particle physics. And now the problems in this field urgently require further development.

Of course, in a very large number of problems these investigations do not in any way replace those made with accelerators. Their mission is to discover new facts in the region inaccessible to accelerators, sometimes determining only the relatively rough characteristics of the processes. In relation to the problem of accelerator technology development, cosmic-ray studies play the role of "prospectors" who help to make clear the main paths of future work with accelerators, and who in particular substantiate the necessity for building accelerators.

Translated by C. S. Robinson